CHARACTERIZING COMPRESSED EARTH BRICKS BASED ON HYGROTHERMAL AGING AND WIND-DRIVEN RAIN EROSION

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
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To my wife, Michele and my daughters Rachel, Leah and Tasha

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The rapidly increasing demand for affordable housing in developing countries has highlighted the need for sustainable housing options, especially given the inadequate supply of traditional building materials. While advances in the design and use of compressed earth bricks (CEBs) present a viable solution to this dilemma, there have been significant concerns about their durability in tropical environments. The objective of this research is to evaluate the durability of CEBs using hygrothermal aging and wind-driven rain (WDR) erosion tests. Hygrothermal aging was performed by exposing different CEBs samples to 100°C and 100% humidity for 7 days and then conducting an analysis using scanning electron microscopy (EDS), which determined that Soil Cement CEB showed the least deviation in the chemical reaction of the focal elements. The WDR erosion test revealed that the soil cement CEB had the least erosion from the rest of the CEBs. In conclusion, the stability of CEBs appears to vary depending on the constituent ingredients and stabilization techniques used. Based on this research it was shown that there is a correlation between elemental composition and erosion levels of

the CEBs. The CEB that has the least microstructural change at the elemental level had the least erosion levels from the exposure to WDR acceleration.

CHAPTER 1
INTRODUCTION

In recent years, developing nations have been facing an exponential demand for affordable housing, for which neither conventional industrialized techniques nor traditional industrial building materials like brick, concrete and steel are in adequate supply (Minke, 2006). Current conditions have been worsening; conventional building materials have remained scarce, housing demand has risen and the urgency to provide immediate practical solutions have become more acute.

Adequate shelter is one of the most important basic human needs, and provisions of housing for low-income populations have been a very difficult requirement to meet, since land and construction costs are typically beyond the means of both the rural and urban poor (Adam, 2001). It is therefore necessary to seek ways to reduce construction costs, as well as implementing sustainable and effective solutions. Such objectives can be achieved partially through the production and use of locally available earth as a principal building material (Minke, 2006) and the promotion of building with compressed earth bricks (CEBs).

Earth as a natural building material is practical and affordable, and it is available in most regions of the world. Earth is frequently used and transformed in place, and can be obtained directly from the footprint building site, making its use even more appropriate due to the significant reduction or elimination of transportation costs. Further, earth has several key advantages over more conventional building materials as it is an inherently ecologically material, it has excellent thermal mass properties that can maintain comfortable interior temperatures within dwellings, granaries and other structures without the need for mechanical heating or cooling. Additionally, using earth as a building material requires little embodied energy for its processing, and earth structures are virtually entirely recyclable. At the end of its life cycle, as Rael (2008) notes, “earthen buildings simply melt back into the ground, and their ruins can be used to grow vegetation or be reused again as a building material”, reducing construction waste and the need for construction and demolition landfills. Lastly, the local population benefits from more direct and indirect employment opportunities through the use of earth-based construction techniques over imported and other industrial construction materials.

Despite the above advantages, CEBs do have some deficiencies, especially when used in tropical environments, characterized by frequent and intense rainfall and long periods of high relative humidity which prematurely compromise their integrity. This is due to the fact that CEBs are produced mainly from soil as the bulk ingredient, which is notorious for being prone to erosion and disintegration in water. Under the severe conditions often experienced in the humid tropics, soil-based bricks often show considerable defects even over short periods of time. Consequently, the maintenance costs or even early rebuilding costs of deteriorated CEBs structures in such environments are undesirable and unsustainable.

Because of the huge potential for CEB use in all climates, including those with high rainfall and high ambient humidity, studying the durability of CEBs of varying composition is a major research concern, since increasing the long-term durability of the bricks can be the key to their widespread implementation and acceptance in geographical regions where affordable housing is desperately needed.

The research discussed in this paper is a subset of a NSF-funded SGER: “Optimizing the Hygrothermal Performance of Earth Bricks in Hot and Humid Climates”. A project carried out in Tanzania and the United States (University of Florida) in 2008-2010. This thesis focuses on the hygrothermal aging and WDR erosion experiments carried out at the University of Florida in 2010. Background information and various aspects of research activities and results can be accessed at: http://web.dcp.ufl.edu/obonyo/SGERResearch.html.

The aim of this thesis is to characterize hygrothermal aging and wind driven rain erosion in CEBs of several common compositions through laboratory acceleration test methods. The specific objectives of this research are:

1. Conduct a literature review of CEBs and assess the factors affecting deterioration, specifically, hygrothermal aging and wind driven rain erosion.
2. Evaluate the hygrothermal performance of several compositions of CEBs.
3. Conduct an accelerated test to simulate wind-driven rain erosion on these CEBs.

Chapter 2 contains a literature review that addresses earth building techniques, factors affecting the deterioration of CEBs, and stabilization techniques for CEBs. Chapter 3 provides the methodology used to conduct this research. Chapter 4 provides the results of the laboratory experiments performed. Finally, Chapter 5 discusses and analyzes the laboratory results, provides a conclusion of the research and results, and provides recommendations for further research.

CHAPTER 2
LITERATURE REVIEW

Earth as a construction material has been used for thousands of years by civilizations all over the world. Many different techniques and methods have been developed, which vary according to the local climate and environment, as well as local traditions and customs (Houben & Guillaud, 1994). Globally, and in most hot-arid and temperate climates, earth has been widely used as the preferred building material for vernacular architecture. Even today, academics, authors, builders, writers and architects have noted that between one-third and one-half of the population of the planet lives in buildings constructed of earth (Rael, 2008). Traditional earth construction materials have proven to be suitable for a wide range of buildings, and with earth being one of the few abundant materials that has not gone through the process of industrialization, it has a great potential for increased use in the future of ecologically and economically sustainable construction and development; by disseminating a modern and progressive approach in areas where earth construction has been considered less successful as it has been in hot and humid climates (Houben & Guillaud, 1994).

While traditional earth architecture presents several challenges due to climatic variability, compressed and stabilized earth bricks offer a potential remedy for many of today’s needs and future demands. In particular, extending the knowhow of using CEBs could indeed be implemented for a foundation for Rural and Urban Sustainable Engineering of the developing nations and their diverse and growing populations.

2.1 Advantages and Disadvantages of Building with Earth

The perceived hegemony of the industrialized world has for decades been directly responsible for causing an inferiority complex among earth-building cultures. Today, the most common building material on the planet is classified as “alternative” or worse, “primitive” (Rael, 2008). At the dawn of every country’s transition to an industrialized society, the phenomenon of abandoning its earth-building traditions creates a significant risk of depleting precious natural resources such as forest wood used for brick firing and an unsustainable and unaffordable investment in construction projects using , industrially-produced materials such as concrete, which “often performs poorly in developing nations” (Adam, 2001), and in doing so, also causes the regrettable loss of traditional cultural knowledge and heritage.

While it is true that the makeup of soil, which differs from one place to another, makes it difficult to create material standards for earth and building codes for earth buildings (Rael, 2008), its potential cannot be overlooked with the considerable benefits of earth construction, namely ecological and economic sustainability.

2.1.1 Advantages

Given the long-term vitality of soil-based construction materials in human history, it is not surprising that these materials offer several advantages, some of which have been alluded to in earlier sections. The principal advantages of CEBs include their ability to insulate against thermal extremes, their very low cost of construction and transportation, greatly reduced environmental pollution, their recyclability; their relatively low technological complexity (which allows for do-it-yourself construction); and their marked preservation of timber and other materials, reducing ecological degradation through mining and deforestation (Minke, 2006).

Soil is available in large quantities in most regions of the world and is easily accessible to low-income groups. In some locations, earth is the only material available and it requires simple, low-cost equipment to produce building materials. Even with the addition of stabilizers does not drastically weaken these key advantages, and CEBs are suitable as a construction material for the majority of many common architectural designs. Lastly, CEBs are highly competitive against their more conventional alternatives in their fire resistance and are virtually non-combustible (Adam, 2001).

2.1.2 Disadvantages

The perceived lack of durability of earth building techniques has created a barrier to its use and adaptation in modern construction industries. Physical disadvantages of building materials constructed from soil commonly include their reduced durability if not regularly maintained and properly protected, particularly in areas affected by medium to high rainfall, their low tensile strength (being particularly poor in their resistance to bending moments and seismic activity, and their limited applicability only in compression (e.g. bearing walls, domes and vaults), their low resistance to abrasion and impact if not sufficiently reinforced or protected, and perhaps most notably their low acceptability amongst most social groups (being considered by many to be a second class and generally inferior building material).

On account of these problems, earth as a building material lacks institutional acceptability in most countries and as a result building codes and performance standards have not been fully developed, despite highly redeeming qualities and potential for technological development through stabilization techniques and augmented construction (Adam, 2001).

2.2 Earth Building Techniques

2.2.1 Earth Building Techniques

The following sections will discuss different types of earth-building techniques. These include rammed earth, molded earth, adobe molding, stacked earth, and compressed earth bricks. The relative strengths and weaknesses of each technique will also be discussed.

2.2.1 Rammed Earth

Earth construction and techniques have been known for over 9000 years. Earth was used as the primary building material in all early ancient cultures for homes and communal structures. Early Stone and Bronze Age archeological remains found in China are rammed earth structures. Further, the technique can be traced across the world and throughout history. Indeed, compressed soil-based architecture is known to have been utilized on all human-occupied continents, and in every early human culture, with examples being known from all kinds of human-occupied and agricultural structures such as farms, granaries, houses, chateaux and fortresses (Figure 2-1). Rammed earth structures include entire villages in North Africa, the majority of the Great Wall of China, most buildings in the Himalayan regions of Tibet, Bhutan, Nepal and Ladakh, and widespread examples from native North and South America (Minke, 2006).

Modern rammed earth is also often known by its French name, *pisé de terre*, which was first used in Lyon, France, in 1562. In this technique, earth is compressed between parallel wooden plates that are later removed and are extended farther to work on another section of the wall (Figure 2-2). A slightly dampened mixture of earth containing appropriate amount of clay, grit and sand is poured into the molds or formwork one layer at a time and compressed in place to form a homogenous monolith wall (Rael, 2008).

As with all earth construction techniques, the process begins with soil selection. The soil necessary for rammed earth building techniques is preferably sandy or gravely rather than clayey. Once excavated, the soil is thoroughly sieved and the larger rocks are removed. If the natural soil is too dry, it should be moistened and mixed to produce a uniformly damp mixture. The mixture is then poured into a form in thin layers and then rammed to increase its density. The resulting structure is highly stable in most circumstances (Auroville, 2011).

Technologically advanced techniques are based on the same principles, though the traditional wooden rammer has been replaced by pneumatic rammers, and the heavy wooden formworks have evolved into light composite ones, made of plywood, steel or aluminum. Pneumatic rammers, dump loaders, mixers, ban conveyors, etc., have been introduced, which have allowed for faster building and provide a finish of more consistent quality (Auroville, 2011). Furthermore, rammed earth has spread to regions where it is not vernacular, and where traditional techniques have been lost due to performance requirements of local regulatory building codes. Technical standards have been prescribed by experts in the field where an ideal mixture is 15 to 18 percent clay mixed with 23 percent coarse aggregate, 30 percent sand, and 32 percent silt: but because clay provides good cohesion, mixes with up to 30 percent clay are possible (Rael, 2008).

2.2.2 Molded Earth

Direct shaping makes use of plastic earth and does not require a mold or formwork. Plastic earth is shaped, much as a potter would do it. The quality of the soil, its preparation and the water consistency are known only to the builders, and is highly variable. This technique also allows for a very fluid and varied architecture. This technique requires that builders have the proper knowledge regarding soil quality in order to control shrinkage as the walls dry, and is indeed an art form (Figure 2-3).

The molded earth technique has been and is still used a great deal in Africa, in the Sahel, as well as in many equatorial regions. Beautiful examples can be seen in Cameroon, where shaped earth has been used for houses and granaries. Natural and traditional stabilizers have been used in countries like Nigeria and Ghana, and other countries of this region. Builders either used plants or vegetable juice, or boiled seeds or other plant parts to prepare natural glues, which were then added to the soil. Unfortunately, most of this knowledge has been lost over the years under the guise of "modern development", and many of these construction techniques are extinct or endangered, becoming increasingly scarce over time.

2.2.3 Adobe Molding

Sundried clay brick, called adobe, is undoubtedly one of the oldest building materials used by humankind, with the oldest identified adobes produced around 9,000 BC at Dja' De El Mughara in Syria. Adobe bricks are made of thick, malleable mud, often with straw added. After being cast, they are left to dry in the sun. They are traditionally either hand-shaped or shaped in parallel piped wooden molds (Figure 2-4).

The Spanish name *adobe* comes from the Egyptian hieroglyph (Figure 2-5), meaning brick. It has passed via Coptic as "τωωβε" in Arabic, as "*al-ţŭb*". When Arabs invaded Spain and France, the word evolved gradually as "*a thob*", then "*a dob*", until it became finally "*adobe*" in modern Spanish. It was then incorporated into French and English.

The adobe technique is made either by filling molds with a pasty soil mixture or by throwing moist lumps of earth into them (Figure 2-6). Different types and sizes of molds can be used, and are usually made from timber. The throwing technique is commonly used in all developing countries. The greater the force with which the mixture is thrown, the better its compaction and dry strength. The surface is smoothed either by hand or by a timber piece, trowel or wire partition and stacking. One person can typically produce between 300 and 500 bricks per day. Adobe, as ancient as it is, it is still used around the globe, and its production has been industrialized, standardized and codified by many local building authorities (Minke 2006).

2.2.4 Stacked Earth (Cob)

Plastic soil is usually formed in balls, which are freshly stacked one on top of the other. This technique was used often in Europe, where it was named “cob” in England and “*bauge”* in France. This technique is still used in Africa, India and in Saudi Arabia, where elaborated architectural examples can be seen. Shibam, the historic capital of Southern Yemen, was built with a combination of cob and adobe (Figure 2-7). It has been dubbed “The Manhattan of the Desert”, and recorded by the United Nations Educational, Scientific and Cultural Organisation as a world heritage site (Auroville 2011).

2.2.5 Compressed Earth Bricks (CEB)

With the advent of the industrial revolution, natural earth construction techniques dwindled, but following the Second World War, material and resource shortages brought earth construction back as a possible compensation for many construction needs. With the introduction of massive road construction, techniques for earth stabilization with cement were developed and implemented. These techniques carried over to traditional earth brick production, increasing its density and making CEBs stronger and more durable. The late 1980s saw a significant interest in CEBs in both developed and developing countries. This increased interest in CEBs came at a time when the construction sector was developing performance based specifications for building materials (Heathcote, 2007).

2.3 Factors affecting the deterioration of CEBs

Naturally, the usefulness of CEBs depends on the durability of the bricks themselves. Durability as defined by Kerali (2000) is "the ability of a building material and its parts to perform its required function over a period of time." Any building material when exposed to the environment undergoes deterioration over a period of time, and the rate of deterioration affecting a material can be internal and external (Avrami et al., 2008). The internal factors that affect deterioration could be related to material composition and production methods and the external factors causing deterioration from environmental influences. These often act on a material simultaneously and manifest themselves in the form of physical, chemical and biological deterioration (Kuhnel, 2004).

2.3.1 Physical, Chemical, and Biological Deterioration

There are several factors that cause CEBs to physically deteriorate. These include fluctuating temperatures, which often act together with ambient air humidity, ground moisture, and rain. This results in the weakening of intragranular bonds which in turn causes fissures in the block fabric and makes the blocks more susceptible to weathering (Kuhnel, 2004). Bricks that are susceptible to weathering are more prone to water absorption, further accelerating the degradation process.

Absorption of water causes swelling in the fabric and evaporation causes shrinkage in the block (Ren and Kagi,1995). As water percolates, any unstabilized portion can be expected to dissolve, thus leading to softening of the earth fabric with a direct impact on the surface strength. Any loose material on the surface of the block is usually washed away with this force, causing pitting in the blocks, which makes them vulnerable to further erosion (Kerali, 2000). Heathcote (2002) in his study showed that the predominant cause of deterioration of earth walls was due to erosion caused by WDR. Temperature fluctuation is also responsible for causing physical deterioration in the CEBs. Such fluctuations can occur in ambient temperatures or can be caused by direct sunlight and the resulting thermal loading, both of which result in expansion, but also contraction through shrinkage and drying of the brick fabric (Kerali, 2000). Consequently, there is a fractional reduction in the volume of the bricks, destabilizing the structures built thereof.

Deterioration in CEBs can also be caused due to chemical activity which includes the deterioration due to sulphate attack from acid rain, chemical leaching, and salt crystallization of the CEBs (Larbi, 2004).

2.3.2 Hygrothermal Deterioration

Deterioration of CEBs due to moisture absorption and temperature change can be defined as hygrothermal deterioration. The service life of CEBs is strongly related with how the material composition of the CEBs respond to heat, air, and moisture absorption changes (Kunzel, 1995). CEBs can be characterized as being comprised of only a few components, each with an expected performance capability to withstand moisture and recurring water penetration dependent and independent on the climatic conditions in which the CEBs are used. The mechanisms by which CEBs redistribute and transport moisture must be taken into consideration for the potential for moisture induced damages (Karagiozis, 2002). Since water is a solvent, all CEBs will eventually have water related damage, some will be as soon as they have been built while others may take a considerable time. However, the water contained in the original brick will also dry out, and this dehydration will affect its strength. The drying rate of a CEB depends on the loads to which the CEBs has been exposed and drying rate performance characteristic combine with water penetration represent hygrothermal performance (Karagiozis, 2002). Hygrothermal loads on the other hand, include contributions from loads caused by wind-driven rain, mechanical pressures, wind-pressures, stack effect, vapor diffusion, liquid diffusion, sorption and suction storage, and temperature-dependent sorption capabilities as well as evaporation-condensation characteristics. At all times, the thermal transport is fully coupled to moisture transport and can be related to the quality and durability of the materials and their associated mechanical, chemical, and hygrothermal properties which are a variable function of time and the environment to which they are exposed (Karagiozis, 2002).

2.3.3 Wind-Driven Rain Erosion

When wind occurs simultaneously with rain, it causes an angled rainfall vector which is scientifically defined as either “driving rain” or “wind-driven rain” (WDR). WDR research is governed by a range of parameters including environment topology, wind speed, wind direction, turbulence intensity, rainfall intensity, raindrop size distribution and rain event duration. This large number of parameters and their variability make the quantification of WDR an extremely complex area of research. Field experimental methods and measurements of WDR science have virtually remained unchanged since the 1930s and have been commonly performed for research purposes only (Blocken and Carmeliet, 2004).

Simulation research was conducted by Cytrin who developed a rain simulation test in 1955 to evaluate the resistance to the forces of driving rain setting up a format of water pressure and exposure to time suggesting an equivalent factor of 10 years of rainfall. In 1970, Wolfskill developed a shower spray test in which he measured the erosion of stabilized soils and correlated the depth of the pitting to the capacity of the tested soil to withstand rainfall. In 1987, Reddy and Jagadish expanded Wolfskill's principles, but developed a soil ratio measuring the test erosion depth related to rain precipitation (Heathcote, 2002).

In 1990, Ola and Mbata developed a vertical spray test with pressures ranging from 6 psi to 65 psi and water flows of 2 gallons per minute to 12.25 gallons per minute respectively, and correlating to annual rainfalls of 25 inches to 275 inches in a period of 50 years. Their experiment also showed that erosion decreased when specimens' compaction and /or cement content were increased (Heathcote, 2002).

In the 1970s, an increased interest in earth-based construction motivated the Commonwealth Experimental Building Station in Australia to develop an accelerated erosion test referred to as the "Bulletin 5" accelerated erosion test , which is the name of the document. The test is based on spraying the face of a sample for a period of one hour or until the sample is penetrated (Heathcote, 2002).

"Bulletin 5" test is performed with water pressurized at 7 psi and delivered though a horizontally mounted nozzle. Specimens are mounted in the rig in the same orientation as proposed for wall construction. A shield ensures that only a limited area of block face is subjected to the water spray. During testing, the spray may be stopped every 15 min to assess performance. The depth of pitting is measured using a 3/8in diameter flat-ended rod. The erosion rate is expressed as the pitting depth per minute of exposure time (Walker, 2004).

2.4 Principles of Stabilization

2.4.1 Soil Stabilization

In the field of road construction, techniques of improving soil durability with additives that modify soil properties have been used widely since the 1920s. These techniques, known as soil stabilization techniques, have the effect of increasing durability and creating erosion-resistant soil. The result is structures that can withstand the impact of a variety of damaging environmental influences, such as temperature fluctuations, humidity, moisture and mechanical pressure.

Differences in the durability of soil that has been stabilized can be significant, as reported by Adam: “Resistance can help prevent structural failures brought about by clay and silt expansion and contraction, which can cause crumbling of surface coatings. Further, the strength of a soil can be increased 400% to 500% with the use of the correct method for stabilization.” (Adam, 2001). Particularly effective strategies of soil stabilization include increasing the soil density as well as adding stabilizing agents, which either react with the soil grains or bind them together (Adam, 2001).

2.4.2 Principles of CEB Stabilization

The strength of CEBs is also strongly affected by quality control procedures. These range from soil sampling practices to methods of manufacturing. Attention to a wide variety of factors is required: for example, the strength and durability of bricks can be improved through soil testing, gradation, optimum amount of clay in the soil, optimum amount of water while making the bricks, compression force applied and curing conditions. The primary ingredient that allows a soil to be used effectively in construction is clay, which offers a cohesive effect by binding other fractions. However, the tendency of clay to disintegrate can be problematic, which is why stabilization techniques are so important for the durability of CEBs (Adam, 2001).

2.4.3 CEBs and Mechanical Stabilization

A technique for stabilizing CEBs is known as mechanical stabilization. This refers to the use of machines to compact and compress bricks, which reduces the air void volume in the CEBs. By increasing soil density, compacting and compression makes the bricks more resistant to wind and rain erosion. During this process, attention must be paid to the type and proportions of soil used, the moisture content during compaction, and the effort applied in compression, because each of these factors has a significant effect on the resulting density and durability of the CEBs. In particular, mechanical stabilization aims to achieve the correct proportions of sand and clay so that the bricks will be less permeable and thus more durable. Specific methods of mechanical stabilization include foot treading as well as the use of hand tamping equipment. These methods can achieve compacting pressures ranging as high as several thousand MN/m2 as a result of using mechanical equipment. (Adam, 2001).

2.4.3 CEB Stabilization Techniques Using Machines

There are three types of manual presses that can be used with CEBs. These presses trace their origins to a device commonly known as the CINVA-Ram, which is made up of a steel box and a lever (Rael, 2008). These three presses all share the same basic design as the CINVA-Ram: the light mechanical press, the light hydraulic press, and the heavy mechanical press.

Light mechanical presses are relatively easy to construct and to repair. Other strengths of this type of press include being lightweight, easy to use, cost-efficient and durable. Although they usually have only one molding module that can exert low pressures, they are still one of the best available presses of their type, which is why many countries manufacture and use them despite their low production output (Houben and Guillaud, 1994).

Another press that is considerably more productive than the CINVA-Ram type is the light hydraulic press. Despite their small size, these presses can apply pressures of up to 10MN/m2 by using a hydraulic piston instead of the swivel and rod system of the CINVA-Ram. As a result, the light hydraulic press can yield CEBs with a density that is as much as 20% greater than regular CEBs, thus allowing for expansive soil compressions. (Houben and Guillaud, 1994).

Finally, there are heavy mechanical presses, which are characterized as industrial-grade. These presses utilize long-lasting pressure and have interchangeable molds. Their design results in greater efficiency, higher compression and density, as well as increased production capacity. (Houben and Guillaud, 1994).

2.4.4 Stabilizers Used in CEBs

There are several types of stabilizing agents that are commonly used in building CEBs. These include cement, lime, bitumen, gypsum, and pozzolanas. Each of these stabilizers will be discussed in the following sections.

2.4.4.1 Cement stabilization

As previously mentioned, compressed earth bricks are particularly susceptible to erosion caused by water. However, adding cement to CEBs helps to make the bricks water-resistant. This happens because the cement actually limits the amount of swelling caused by water, and it also adds strength to the bricks:

> Cementation can make soil water-resistant through the limitation of swelling and the augmentation of compressive strength. When ordinary Portland cement hydrates when water is added, a cementitious gel is produced that is independent of the soil. This gel is made up of calcium silicate hydrates and calcium aluminate hydrates, which make up the bulk of the gel, and hydrated lime, which is deposited as a separate crystalline solid phase. This cementation process—which varies with time, temperature, soil type, and cement type—deposits an insoluble binder between the particles of the soil, which embeds them in a matrix of cemetitious gel. At the same time, the lime released during cement hydration forms additional cementitious bonds as it reacts with the clay particles. (Adam, 2001).

Research suggests that optimal levels of stabilization occur when the bricks contain between 3% and 18% of cement content by weight. The correct percentage of cement to use depends primarily on the soil type, since the amount of linear shrinkage affects the cement content that is needed for stabilization. (Minke, 2006).

2.4.4.2 Lime stabilization

One limitation of using of cement as a stabilizer is that it does not work well with clay soils. However, using lime is a stabilizing agent that can be used effectively to stabilize clay soils. There are several stabilizing effects that lime may have, including cation exchange, flocculation and agglomeration, carbonation, and pozzolanic reactions. The pozzolanic reaction has a particularly stabilizing effect because it binds soil particles together as various cemetitious compounds are formed. The addition of lime serves to make clay less absorbent of water; thus, the clay soil becomes more manageable and less susceptible to variations in moisture content (Adam, 2001). Minke (2006) offers this description of the stabilizing effects of lime:

If there is sufficient humidity, then an exchange of ions takes place in the loam with lime as stabilizer. The calcium ions of the lime are exchanged with the metallic ions of the clay. As a result, stronger agglomerations of fine particles occur, hindering the penetration of water. Furthermore, the lime reacts with the CO2 in the air to form limestone. (Minke, 2006) Therefore, lime can also be used as a stabilizer in CEBs.

2.4.4.3 Other stabilizers

There are several other stabilizers that can be used in CEBs. For example, bitumen is ideal for sandy soils. In granular soils, it is possible to increase both the cohesion and strength of earth bricks by adding even small amounts of bitumen (2-6%). Another advantage of bitumen is that it repels water. Some soil types may experience both of these advantages to differing extents. However, the amount of bitumen needed for clay soils is quite large. There are also several disadvantages to using bitumen: for example, “in most developing countries, bituminous materials are not traditional, are expensive to import and transport, require heating, storing and preparation which increase costs; and in hot climates, heat can have an adverse effect on their binding properties” (Adam, 2001).

Yet another stabilizing ingredient is gypsum, which is a material that has been traditionally used in many Mediterranean and Middle Eastern countries, especially in early civilizations. Gypsum works particularly well as a stabilizer for sandy soils. Finally, pozzolanas can also be used, and they are most effective when combined with hydrated lime. These substances are found naturally in volcanic ash or pumice;

alternatively, they can be produced from finely ground recycled fire clay bricks and mudstone. Pozzolanas are notably rich in silica and alumina. (Adam, 2001).

2.5 Summary

From the above literature review, a number of conclusions can be made. Earth-based construction technology has a long history; technologies like adobe, rammed earth, molded earth and stacked earth, have been successful in hot and arid climates throughout the world and for millennia.

The review also shows that when CEBs are stabilized, they improve their physical structure and behave better in humid climates as compared to other methods of building. It is also established that even under normal conditions, durability of the CEBs will be affected by environmental exposure. This condition worsens when the bricks are exposed to hygrothermal conditions and WDR, since the primary agents that weaken the brick fabric are water, temperature, and chemical action within the brick. Water-related action causes the brick fabric to weaken due to factors like wetting and surface abrasion due to rainwater. When combined with temperature fluctuations, this causes the fabric to weaken further, resulting in cracks in the bricks. The literature review shows that when soil is mechanically stabilized, particularly with cement and other additives, it increases the strength and durability of the bricks to some extent, depending on the combination of additives and soil selection. Hygrothermal aging and WDR erosion testing provide the investigation of how specific changes occur and how the environment affects CEBs in the field in an accelerated research format.

Figure 2-1. Castillo,10th century (Auroville Earth Institute, 2011).

Figure 2-2. Manual rammed earth technique (Auroville Earth Institute, 2011).

Figure 2-3. Shaping a granary, Nigeria (Auroville Earth Institute, 2011).

Figure 2-4. Hieroglyph, Egypt (Auroville Earth Institute, 2011).

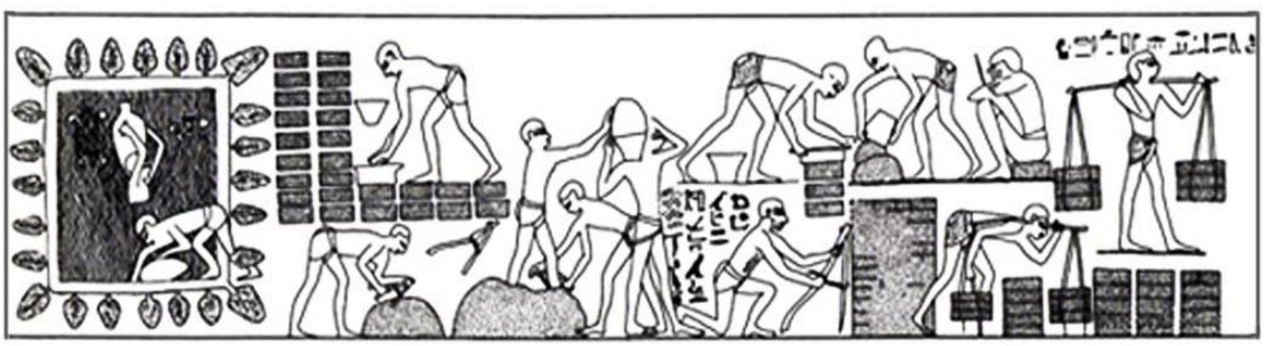

Figure 2-5. Tomb of Queen Hatshepsut, Egypt (Auroville Earth Institute, 2011).

Figure 2-6. Handmade adobe, India (Auroville Earth Institute, 2011).

Figure 2-7. “Manhattan of the desert", Yemen (Auroville Earth Institute, 2011).

CHAPTER 3
METHODOLOGY

The objectives of this study are: 1) The characterization of four types of CBSs that were subjected to hygrothermal aging, and 2) Conduct and evaluate an accelerated test to simulate wind-driven rain erosion on CEBs based on the Bulletin 5 test rig.

To evaluate the hygrothermal impacts to the CEBs, scanning electron microscope (SEM) and Energy dispersive X-ray analysis (EDS) were utilized. “EDS is a technique used to identify the elemental composition of a sample or small area of interest on the sample. During EDS, a sample is exposed to an electron beam inside a SEM. These electrons collide with the electrons within the sample, causing some of them to be knocked out of their orbits. The vacated positions are filled by higher energy electrons which emit x-rays in the process. By analyzing the emitted x-rays, the elemental composition of the sample can be determined tracking changes in minerals that were known to be originally present” (Sem Lab,Inc.).

3.1 CEB Formulation and Fabrication

The NSF-funded SGER project concluded that the optimum formulations for the fabrication of the CEBs used in this study were: 1) Soil Cement Lime Fluid: 100lb of soil, 5lb of cement, 5lb of lime 2.5lb of Aeonian Brick Stabilizer, 2) Soil Cement: 100lb of soil, 7lb of cement, 3) Soil Cement Lime: 100lb of soil, 5lb of cement, 7lb of lime, 4) Soil Cement Fiber: 100lb of soil, 5lb of, cement, 1lb of fiber (Table 3-1). Therefore these four CEB formulations were used in this research and a fifth brick: a factory produced interlocking brick was also included in the research as a control. The CEBs were fabricated using a Terra Block manual block press based on the CinvaRam design (Figure3-2). The CEBs were tested for compressive strength (Table 3-2).

3.2 Hygrothermal Aging

Many studies in this area conduct testing on hygrothermal aging by quantifying the impact of cyclic loading. Specimens are therefore assessed following exposure to wet and dry cycles (Obonyo, 2011). In this study, the focus was on the water-induced chemical changes following exposure to heat. To achieve this goal, the specimens were aged through being subjected to elevated heat and moisture conditions based on the provisions of the ASTM C1560-03 Standard Test Method for Hot Water Accelerated Aging of Glass-Fiber Reinforced Cement-Based Composites.

The hygrothermal aging performance of the CEB types as outlined in section 3.1 were assessed by placing them in a climate control chamber. The specimens were first cut in a 2in by 2in by 1in cubes out of a whole brick then placed in water and exposed to high temperature (100°C) and (100% humidity) for 7 days. The samples were subsequently dried, and then crushed using a pestle and mortar prior to SEM/EDS analysis to determine the extent of chemical composition alteration resulting from the hygrothermal aging process. The SEM/EDS characterization was conducted using a JEOL Scanning electron microscope model 6400 (Figure 3-2) at the Major Analytical Instrumentation Center (MAIC), at the University of Florida. The chemical reactions that were expected to take place were based on the mineral composition of the CEBs(Table 3-3).

3.3 WDR Erosion

The WDR erosion accelerated testing rig used in this study is a modified version assembled for experimental and preliminary testing based on an adaptation of the UTS using provisions of various ASTM Standard Erosion Testing. The three tests employed in this study were the Cavitation Erosion Test using vibratory apparatus (ASTM G-32), the Liquid Impingement Erosion Test (ASTM G-73), and the Erosion of Solid Materials by a Cavitating Liquid Jet Test (ASTM G-134). Precedence for this approach can be found in the accelerated erosion testing done on different materials by Dynaflow, Inc. (Dynaflow, Inc., 2011; Obonyo, 2011).

Figure 3-3 shows a schematic of the test rig for this research and figure 3-4 shows a working modified “Bulletin 5” UTS developed by Heathcote.

The following modifications were made to the Bulletin 5 rig: a pressure washer was used instead of a high flow water pump, and the component of the pressure washer were adapted to measure psi pressure and a release valve was used to control water flow and reduce pressure (Figures 3-5, 3-6,3-7).

The specimens were placed with their external face surface exposed to four inch diameter water spray the nozzle tip of the pressure washer’s jet nozzle, with a cone spray nozzle setting. The nozzle was positioned 20 inches from the face of the samples and water was sprayed at a setting of 300psi and 40 gallon per hour water flow and 600psi with 60 gallons per hour water flow respectively, to verify two levels/strengths. Readings are taken every 15 minutes to establish the depth of erosion to assess the resilience of the five brick types.

Depth of erosion was measured with a visual inspection for pitting and a .25in rod was placed in the cavity and marked at the original brick’s face level for deeper erosion levels.

Table 3-1. Mix design for the bricks

Types of brick	Mixing proportion	Proportion in lb
Soil Cement	14.3:1'(soil: cement)	100lb of soil : 7lb of cement
Soil Cement Lime	20:1:1.4' (Soil :Cement: lime)	100lb of soil : 5lb of cement : 7lb of lime
Soil Cement Fiber	20:1:0.2' (Soil :Cement: fiber)	100lb of soil : 5lb of cement : 1lb of fiber
Soil Cement Lime Fluid	20:1:1:0.5' (Soil: cement: lime: fluid)	100lb of soil : 5lb of cement : 5lb of lime 2.5lb of Aeonian fluid

Table 3-2 Compressive strength of the bricks

Types of Brick	Compressive strength (psi)
Soil Cement	1100
Soil Cement Lime	1200
Interlocking Block	1400
Soil Cement Fiber	1150
Soil-Cement-lime-fluid	1000

Table 3-3. Mineral composition of materials

Materials	Mineral composition
Lime (hydrated)	Calcium, Oxygen, Calcium Hydroxide
Portland Cement	Tricalcium Silicate, Dicalcium Silicate, Tricalcium Aluminate and Calcium aluminoferrite
Soil	Fe, Al, Phosphate, Inorganic Phosphorus, Aloxides, and apatite

Figure 3-1. CINVA type CEB manual machine (Terra Block, 2011)

Figure 3-2. JEOL scanning electron microscope model 6400 (University of Florida, 2011)

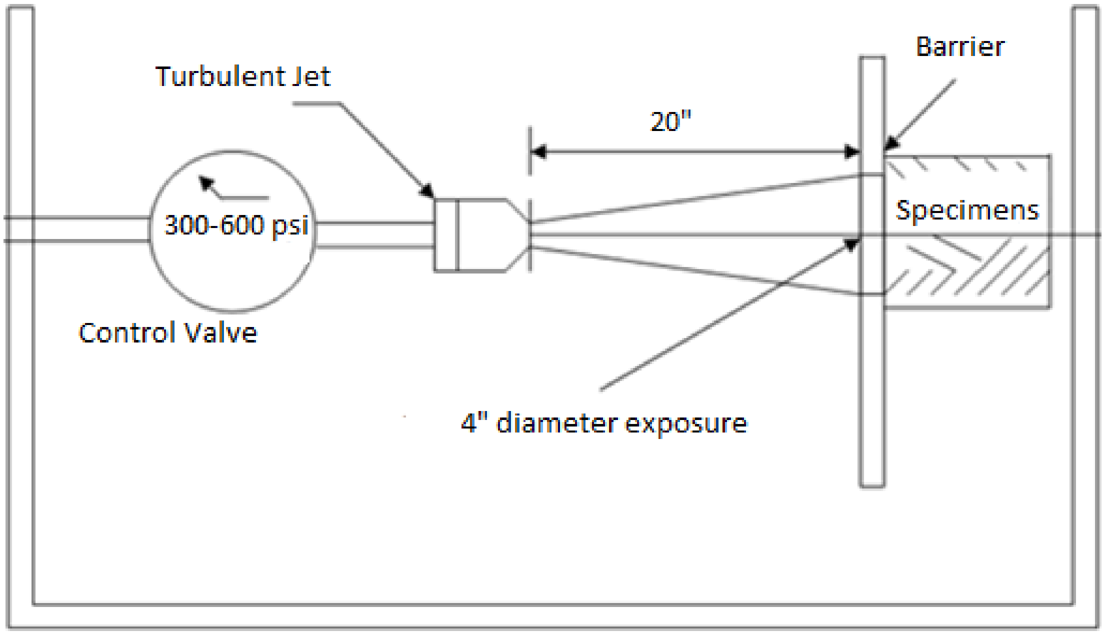

Figure 3-3. Schematic for erosion rig

Figure 3-4. Modified “Bulletin 5” UTS WDR erosion rig (Heathcote, 2002)

Figure 3-5. Experimental WDR erosion rig. Photo courtesy of Joseph Exelbirt.

Figure 3-6. Release valve and psi gauge. Photo courtesy of Joseph Exelbirt


Figure 3-7. Jet nozzle. Photo courtesy of Joseph Exelbirt

CHAPTER 4.
RESULTS

4.1 Hygrothermal Aging

Table 4-1 provides the results from the chemical characterization which identifies the microstructural reactions the samples experienced as the procedure of water immersion and heat exposure to 100°C temperatures in an oven for 7 days. These results show the microstructural profile of the original samples and the changes that occurred to the samples due to the aging process.

Table 4-2 provides an evaluation of the magnitude of change at the elemental level the samples underwent from the aging process with the changes being represented as total percentage of accumulation or loss.

Figure 4-1 and figure 4-2 demonstrates the magnitude of change, the trend of the elemental changes the different CEB types and how some of the gains and losses are significant while others are insignificant.

Upon examination of these tables and graphs, the following can be identified:

The percentage content and microstructural changes that magnesium, aluminum, titanium and iron, displayed, were relatively small and the percentage content and microstructural changes of the remaining elements: carbon, oxygen, silica and calcium, displayed relative higher values and are as follows:

In the soil cement lime fluid CEB the aging process caused a significant loss of carbon and a substantial accumulation of oxygen, remainder elements, silica and calcium show a proportionate increase, although not as considerable.

In the soil cement CEB, the aging process did not trigger significant movement in any of the four mentioned elements.

In the soil cement lime CEB, the aging process caused a significant loss of calcium; in fact, it is the CEB wherein the loss of calcium is most prominent. The remaining three elements of carbon, oxygen and silica, show a proportionate increase, though not drastic.

In the soil cement fiber CEB, the aging process caused significant oxygen and silica loss and a moderate carbon relative proportionate increase; calcium's increase is the most prominent of all the elements in this CEB type.

4.2 WDR Erosion

The purpose of the erosion tests was to determine which bricks would withstand WDR erosion. The test utilized a pressure washer nozzle with two settings: 300 psi of water pressure and 600 psi of water pressure. The result was that only two of the brick types were capable of withstanding the water pressure without significant deterioration. The factory-produced interlocking CEB demonstrated the least degree of erosion, followed by the soil cement CEB which showed minimal cumulative erosion. Thus, the soil cement outperformed the rest of the CEBs that were included in the study. The results of these tests are shown in Table 4-3.

The following sections discuss the results of the tests to measure pitting and erosion, and the accompanying images reveal the depth of erosion and offer visual evidence of the differences in material composition of the CEBs tested. The results will be divided into sections that address each type of brick: soil cement lime fluid, factory produced interlocking, soil cement, soil cement lime and soil cement fiber.

Soil cement lime fluid CEB had an initial erosion depth of 0.6in after the first 15 minutes of exposure to 10 gallons of water stream at the 300psi setting and culminating in 1.0in erosion depth with a total of 40 gallons of water after 60 minute exposure. When exposed to the 600psi setting, the initial erosion depth was 0.7in with a total of 15 gallons of water exposure. At the end of the 60 minute and 60 gallons of water exposure cycle, 1.2in erosion depth was recorded (Figure 4-3).

Factory produced interlocking CEB had a minimal initial erosion depth after the first 15 minutes of exposure to 10 gallons of water stream at the 300psi setting and did not show any pitting after 30 minutes of exposure and 20 gallons of water stream to the remainder of the 60 minute cycle and total water exposure of 40 gallons. Similar results were recorded with minimal initial erosion depth after the first 30 minutes of exposure to 45 gallons of water stream at the 600psi setting and did not show any pitting thereafter to the remainder of the 60 minute cycle and 60 gallons of water exposure (Figure 4-4).

Soil cement CEB had an initial erosion depth of 0.005in after the first 15 minutes of exposure to 10 gallons of water stream at the 300psi setting and culminating in 0.025in erosion depth with a total of 40 gallons of water after 60 minute exposure. When exposed to the 600psi setting, the initial erosion depth was 0.020in with a total of 15 gallons of water exposure. At the end of the 60 minute and 60 gallons of water exposure cycle, 0.035in erosion depth was recorded (Figure 4-5).

Soil cement lime CEB had an initial erosion depth of 0.70in after the first 15 minutes of exposure to 10 gallons of water stream at the 300psi setting and culminating in 0.85in erosion depth with a total of 40 gallons of water after 60 minute exposure. When exposed to the 600psi setting, the initial erosion depth was 0.80in with a total of 15 gallons of water exposure. At the end of the 60 minute and 60 gallons of water exposure cycle, 1.0in erosion depth was recorded (Figure 4-6).

Soil cement fiber CEB had an initial erosion depth of 1.0in after the first 15 minutes of exposure to 10 gallons of water stream at the 300psi setting and culminating in 1.6in erosion depth with a total of 40 gallons of water after 60 minute exposure. When exposed to the 600psi setting, the initial erosion depth was 1.0in with a total of 15 gallons of water exposure. At the end of the 60 minute and 60 gallons of water exposure cycle, 2.2in erosion depth was recorded (Figure 4-7).

Table 4-1. EDS results from hygrothermal aging

Types of Sample	Chemical	Original Samples		Aged Samples	
		Element (%)	Atomic (%)	Element (%)	Atomic (%)
Soil Cement Lime Fluid	C	16.7	24.8	8.8	13.9
	O	45.3	54.4	51.6	63.5
	Mg	1.1	0.9	0.3	0.2
	Al	4.2	3.0	4.5	3.2
	Si	9.0	6.1	10.3	6.9
	Ca	18.4	9.0	21.1	10.8
	Ti	0.6	0.2	1.2	0.5
	Fe	4.3	1.4	1.9	0.7
Soil Cement	C	9.1	14.8	10.2	16.3
	O	51.7	62.8	51.3	61.5
	Mg	1.6	1.2	0.4	0.3
	Al	3.7	2.6	5.4	3.8
	Si	11.2	7.8	13.6	9.3
	Ca	19.7	9.6	15.4	7.4
	Ti	0.3	0.1	0.6	0.2
	Fe	2.1	0.7	2.4	0.8
Soil Cement Lime	C	6.8	11.0	11.1	17.3
	O	50.3	63.8	52.3	61.5
	Al	2.4	1.8	4.3	3.0
	Si	9.9	6.8	15.9	10.5
	S	0.4	0.3	0.6	0.4
	Ca	25.7	13.7	13.3	6.3
	Fe	2.2	0.8	1.8	0.6
Soil Cement Fiber	C	14.7	21.6	17.7	26.5
	O	54.2	59.9	46.5	53.5
	Mg	0.1	0.1	0.1	0.1
	Al	4.3	2.8	4.3	3.0
	Si	21.1	13.3	14.0	9.3
	Ca	3.7	1.6	12.8	5.9
	Ti	0.3	0.1	0.6	0.2
	Fe	1.3	0.4	3.0	1.0

Table 4-2. Evaluation for EDS results from hygrothermal aging

Types of Sample	Chemical	Original Samples Element (%)	Aged Samples Element (%)	Difference Original -Aged (%)	Value of Change (%)
SCLF	C	16.7	8.8	-7.9	-47
SC	C	9.1	10.2	1.1	12
SCL	C	6.8	11.1	4.3	63
SCF	C	14.7	17.7	3	20
SCLF	O	45.3	51.6	6.3	14
SC	O	51.7	51.3	-0.4	-1
SCL	O	50.3	52.3	2	4
SCF	O	54.2	46.5	-7.7	-14
SCLF	Mg	1.1	0.3	-0.8	-73
SC	Mg	1.6	0.4	-1.2	-75
SCL	n/a				
SCF	Mg	0.1	0.1	0	0
SCLF	Al	4.2	4.5	0.3	7
SC	Al	3.7	5.4	1.7	46
SCL	Al	2.4	4.3	1.9	79
SCF	Al	4.3	4.3	0	0
SCLF	Si	9	10.3	1.3	14
SC	Si	11.2	13.6	2.4	21
SCL	Si	9.9	15.9	6	61
SCF	Si	21.1	14	-7.1	-34
SCLF	Ca	18.4	21.1	2.7	15
SC	Ca	19.7	15.4	-4.3	-22
SCL	Ca	25.7	13.3	-12.4	-48
SCF	Ca	3.7	12.8	9.1	246
SCLF	Ti	0.6	1.2	0.6	100
SC	Ti	0.3	0.6	0.3	100
SCL	n/a				
SCF	Ti	0.3	0.6	0.3	100
SCLF	Fe	4.3	1.9	-2.4	-56
SC	Fe	2.1	2.4	0.3	14
SCL	Fe	2.2	1.8	-0.4	-18
SCF	Fe	1.3	3	-1.0	-77

Table 4-3. WDR brick erosion test results

CEB	Pressure (psi)	Distance (in)	Water (gal)	Time (min)	Erosion (inches)
Soil Cement Lime Fluid	600	20	15	15	0.7 in
	600	20	15	30	0.8 in
	600	20	15	45	1.0 in
	600	20	15	60	1.2 in
	300	20	10	15	0.6 in
	300	20	10	30	0.7 in
	300	20	10	45	0.9 in
	300	20	10	60	1.0 in
Factory Produced Interlocking	600	20	15	15	0.005 in
	600	20	15	30	0.010 in
	600	20	15	45	no change in depth
	600	20	15	60	no change in depth
	300	20	10	15	< 0.005 in
	300	20	10	30	no change in depth
	300	20	10	45	no change in depth
	300	20	10	60	no change in depth
Soil Cement	600	20	15	15	0.020 in
	600	20	15	30	0.025 in
	600	20	15	45	0.030 in
	600	20	15	60	0.035 in
	300	20	10	15	0.005 in
	300	20	10	30	0.010 in
	300	20	10	45	0.020 in
	300	20	10	60	0.025 in
Soil Cement Lime	600	20	15	15	0.80 in
	600	20	15	30	0.90 in
	600	20	15	45	0.95 in
	600	20	15	60	1.00 in
	300	20	10	15	0.70in
	300	20	10	30	0.75in
	300	20	10	45	0.80in
	300	20	10	60	0.85in
Soil Cement Fiber	600	20	15	15	1.00 in
	600	20	15	30	1.40 in
	600	20	15	45	1.80 in
	600	20	15	60	2.20 in
	300	20	10	15	1.00 in
	300	20	10	30	1.20 in
	300	20	10	45	1.40 in
	300	20	10	60	1.60 in

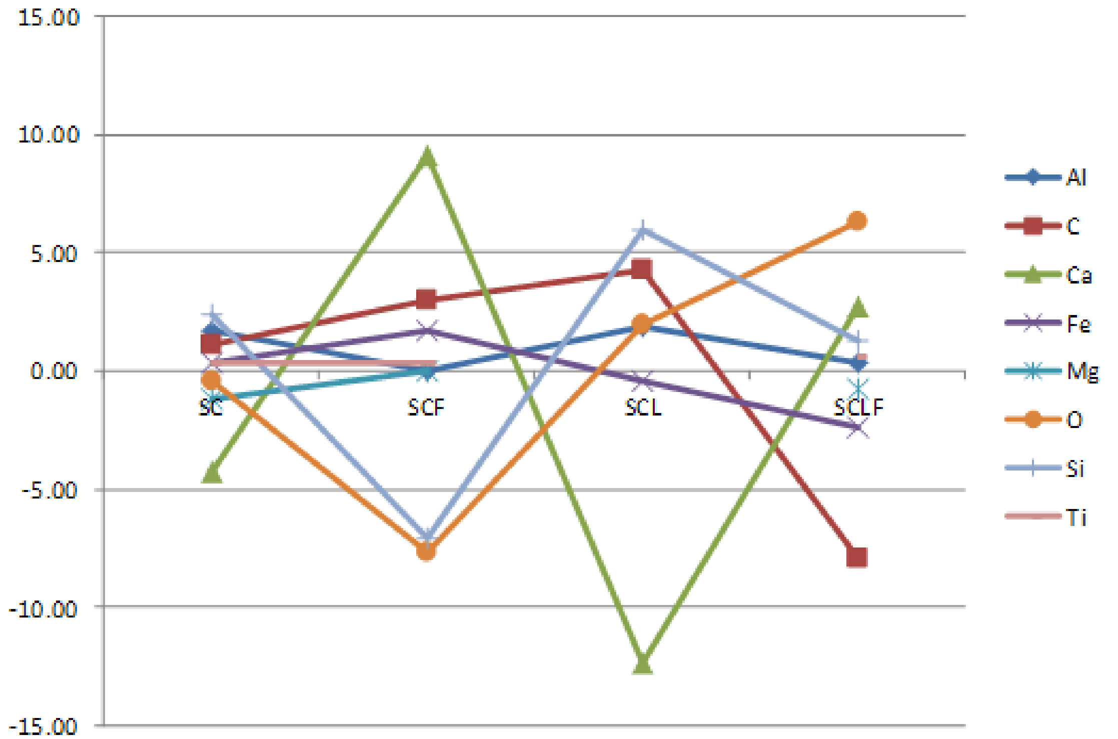

Figure 4-1. Magnitude of change for all elements

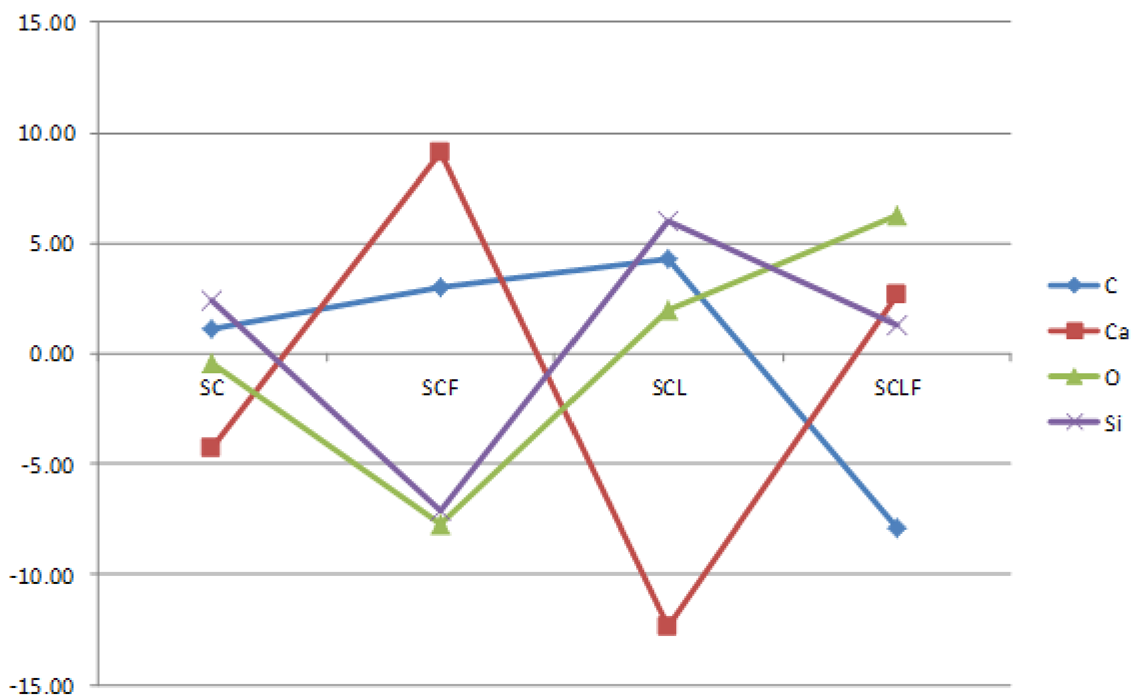

Figure 4-2. Magnitude of change for C, Ca, O, Si

Figure 4-3. Soil cement lime fluid. Photo courtesy of Joseph Exelbirt.

Figure 4-4. Interlocking soil cement lime fluid. Photo courtesy of Joseph Exelbirt.

Figure 4-5. Soil cement. Photo courtesy of Joseph Exelbirt.

Figure 4-6. Soil cement lime. Photo courtesy of Joseph Exelbirt.

Figure 4-7. Soil cement fiber. Photo courtesy of Joseph Exelbirt.

CHAPTER 5
DISCUSSION AND CONCLUSION

5.1 Summary

The principal objective of this thesis was to measure the effects of hygrothermal loads and exposure to wind-driven rain erosion on the performance of different types of CEBs. Practices in the manufacturing of CEBs as well as existing trends and studies in the field of soil stabilization were reviewed. The main concern with the use of earth-based bricks was durability in hot and humid climates with high annual rainfall, a limitation which interferes with the usefulness and expanded use of CEBs in these regions. The performance of CEBs also varies widely according to the makeup of the soil, the manufacturing and stabilization techniques used, and the climate in which they are used. One common concern about the use of CEBs in humid climates is that earth-based bricks may not be able to resist hygrothermal loads and WDR erosion as well as conventional building materials. In order to examine the effects of deterioration and erosion in such environments, this study provided a scenario that aimed to replicate and exceed the conditions found in the humid tropics. A series of CEBs were fabricated based on field parameters, and the durability of these CEBs was then evaluated through accelerated environmental simulations. These simulations enabled the researcher to assess and characterize damage that could potentially be caused by hygrothermal loads of extreme heat and humidity and extreme wind-driven rain (WDR).

5.2 Discussion

The stated objectives in this study were achieved as described in the following sections. The original objectives, as expressed in Chapter 1, were:

1. Conduct a literature review of CEBs

2. Evaluate the effects of hygrothermal aging on CEBs, and
3. Evaluation the effects of wind-driven rain erosion.

5.2.1 Compressed Earth Bricks

A literature review was conducted to explore the history of earth building techniques and to gain a greater understanding of the current trends in earth construction, which are characterized by rapid growth and great potential. This objective was reached through the extensive review of existing literature in Chapter 2. Recent studies about earth construction techniques and current practices in the manufacturing of CEBs, the factors that cause deterioration CEBs, and techniques for soil stabilization were presented.

5.2.2 Evaluate Hygrothermal Performance

Hygrothermal performance of the CEBs was achieved by conducting an accelerated hygrothermal aging procedure that entailed subjecting CEB samples to 100% humidity and 100°C heat to simulate extreme tropical environmental and weather factors affecting CEBs. The EDS results provided data about the microstructural variations from CEB samples that were exposed to aging and contrasted them with virgin samples. Since all samples were exposed to the same test parameters, the variation in the composition of the bricks before and after the test offered evidence of changes due to the exposure to heat and water. These variations in the elements that were recorded during the EDS analysis revealed that the effects of the tests varied by the type of CEB. These varying effects are most likely due to differences in composition of the CEB including the soil and the stabilizers used.

The elements that showed the greatest fluctuations due to the aging process were carbon, oxygen, calcium and silica. These changes did not occur in all of the four sample types, and the detected levels of each element increased in some cases and decreased in others. This is to be expected because the soil type and the presence of stabilizers both influence the ability of the brick to withstand effects of heat and water. Similar results were found by Obonyo when samples were exposed to the same testing parameters:

> The SEM-EDS analysis it is clear that the chemical changes occurring within the microstructure can be directly linked to the existence of specific stabilizers which and how the CEBs reaction to the aging process. For example, the inclusion of lime triggers chemical reactions that increase after one month of exposure increases carbon and calcium while decreasing oxygen and silica. Over the same time period, the chemical reactions that occur when fiber is included in the mix reduce carbon content by over 1/3 while significantly increasing the oxygen, silica and calcium content. Although previous research recommended the inclusion of both lime and fiber for the case study context it is also clear that their use could result in both desirable and undesirable effects depending on how the mineralization of the organic inclusions affects hydration-based chemical reactions (Obonyo 2011).

As Obonyo's research suggests, the composition of the bricks largely determines the fluctuations in constituent elements that will result from exposure to heat and water. For this reason, the composition of CEBs plays an important role in their potential durability.

5.2.3 Simulation of Wind Driven Rain Erosion

The third objective, which was to determine the erosion levels due to WDR, was achieved by conducting accelerated simulation tests with a modified spray rig based on the "Bulletin 5" erosion test procedure. CEB specimens were subjected to the spray test and an analysis was then conducted comparing the rates of erosion on different brick samples.

The results showed that different methods of stabilization affect the capacity of the CEBs to withstand WDR loads. Since the methodology used provided a set of parameters in which the WDR acceleration was constant and the CEB samples differed from one another, the test results also showed that each brick reacted to the loads differently. The CEB that performed the best was the factory-produced interlocking brick, which showed very little erosion. The reason is because it is manufactured with high compression equipment and the soil composition and stabilizer used have been developed for commercial use and high standards.

The soil cement CEB did not perform as well as the factory-produced interlocking CEB, but its performance was exceptional compared to the rest of the CEBs. The reason for this performance can be attributed to the stabilizer chosen, which in this case was cement.

The cement lime and cement lime fluid CEBs performed similarly in the tests conducted, but unlike soil cement bricks, their erosion results show the potential for this type of CEB composition to deteriorate in the field under conditions of wind storms coupled with heavy rains.

As for the soil cement fiber CEB, the erosion was the most significant when compared with the rest of the CEBs. This is most likely because the "natural fibers are highly susceptible to volume changes due to variations in fiber moisture content" (Kosmatka et al., 2002). This has implications for the strength of the chemical bonds: "Fiber volumetric changes that accompany variations in fiber moisture content can drastically affect the bond strength between the fiber and cement matrix" (Kosmatka et al., 2002).

5.3 Conclusions

A number of conclusions can be made from the results of this study. Among the chief historic limitations to the use of CEBs in developing countries of tropical climate are their ability to withstand frequent driving rain and high ambient temperature with high ambient humidity. Due to the fact that insufficient data has existed to document the advantages of some CEB construction methods over others, expansion and increased use of this ancient technology has been slow. By promoting the development of CEB manufacturing techniques, including improved soil selection and more advanced types of manufacturing methods and stabilization techniques, CEBs can have a significant and sustainable impact to the housing needs of the developing nations in tropical climates. Properly stabilized CEBs, with appropriate climate-based technological modifications and adaptations, can be an optimal choice for constructing several types of structures in parts of the world that have been historically unable to utilize this construction material. Due to the readily available and abundant soil supply which conserves natural resources, CEBs' low embodied energy, their insulating capacity to create more stable indoor climates, and their economic advantages over walls made of other industrially manufactured materials such as fired bricks or concrete.

The results from this research support the advancement in the research and improvement of CEBs. Electron microscopically techniques were used to demonstrate preliminary data on the microstructural and chemical changes in CEBs that were triggered by exposure to extreme environmental weather simulation of extreme heat and humidity. The purpose for characterizing these microstructural changes and reactions support the understanding of how the compositions of CEBs withstand extreme climatic exposures.

Further the results for the erosion test provide useful information as to erosion resistance and some predictability to the service life for different types of CEBs. Clearly, CEBs that displayed minor damage caused by the erosion test had a formulation that can be used to benchmark as an exemplary prototype for further research and application. And the performance of CEBs can be optimized through establishing correlations as seen in this study where the CEB with the least erosion had the least elemental variation in the EDS results, thus a direct link between these changes and desirable physical or mechanical properties can be established.

Finaly, these experiments provide a preliminary and experimental tool that can be developed with further scientific research that can be applied to predict life expectancy and the ability to estimate CEB performance and expected service life. As additional data is collected and R&D protocols and testing methods are adopted, CEB construction certainly may expand into parts of the world which could benefit most from this simple, economical and ecologically conservative technology.

5.4 Further Research

This study focused on hygrothermal exposure and the consequential damages to the structure of the bricks tested as well as the potential erosion caused by wind-driven rain. However, further and more comprehensive research should be conducted. For example, similar tests can be conducted on the bricks that are currently stored outside at the Rinker School yard at the University of Florida, a location known for its relatively high humidity and annual rainfall. These CEB have been exposed to natural weathering for more than a year, and these results can be contrasted with the data from this study which employed simulated conditions. Another line of future research could address the effects of alternate stabilizers, such as bitumen, polymers, and chemical additives used in the concrete and road construction industry. There are also additional fiber treatment options that could be investigated, such as fiberglass and treated wood fibers. Protective coatings are another variable that could potentially affect durability and should be studied. Finally, the testing of hygrothermal aging and the resulting chemical changes could be quantified over a longer period of time. This kind of analysis can be used to evaluate the effectiveness of soil selection, stabilizer selection, and method of brick compression, in order to identify the ideal composition of the CEBs, specifically in terms of the correct proportions of earth and stabilizers for each particular soil type.

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BIOGRAPHICAL SKETCH

Joseph Exelbirt was born in Cali Colombia in 1967. At the age of ten, he moved with his family to Israel, and the at age of thirteen they relocated to Miami, Florida where he graduated from North Miami Beach Senior High School and then pursued an undergraduate degree in Political Science at Tel Aviv University in Israel. Upon graduation, he worked in the diamond industry as the quality control officer of a major diamond manufacturer in the Ramat Gan Diamond District. After a brief relocation back to the United States, Joseph returned to Colombia, where he earned an MBA from INALDE, a Harvard-affiliated institution.   Upon reentering the workforce, and advancing though the textile industry for several years, he gained experience from manufacturing of commodity prime materials, to supplying the retail industry. Upon returning to the United States in 1996, he worked in various fields to broaden his professional background and was employment with Dean Witter (finance) and Weichert Best Beach of Miami Beach, FL (real estate). Having a great interest in construction industry, Joseph chose to enter into this occupation from the bottom up, and built his credentials being involved in residential and commercial remodeling projects. This journey led him to Gainesville, FL to pursue a masters degree in sustainable building construction from the University of Florida. With his wife Michelle and three daughters supporting him through the journey, he is looking forward to a vibrant career within an organization committed to sustainable development with aspirations of implementing his expertise in international management and direction.